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Boris Stoyanov
DARK MODULI INSTITUTE

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Boris Stoyanov

DARK MODULI INSTITUTE, Membrane Theory Research Department, 18 King William Street, London, EC4N 7BP, United Kingdom

E-mail: stoyanov@darkmodulinstitute.org

BRANE HEPLAB, Theoretical High Energy Physics Department, East Road, Cambridge, CB1 1BH, United Kingdom

E-mail: stoyanov@braneheplab.org

SUGRA INSTITUTE, 125 Cambridge Park Drive, Suite 301, Cambridge, 02140, Massachusetts, United States

E-mail: stoyanov@sugrainstitute.org

Abstract

A mechanism of supersymmetry breaking known as anomaly mediation in which a conformal anomaly in the auxiliary field of the supergravity multiplet transmits SUSY breaking to the observable sector. There is always an anomaly-mediated contribution to the gaug- ino masses in any hidden-sector model, but where no other direct contribution is present, Anomaly Mediated Supersymmetry Breaking will be the leading effect. Anomaly Mediated Supersymmetry Breaking is another interesting solution to the flavour problem of mSUGRA. Rescaling anomalies in Anomaly Mediated Supersymmetry Breaking is special type of gravity mediated supersymmetry breaking that results being communicated to the supersymmetric Standard Model. The supergravity Lagrangian always give rise to soft mass parameters in the observable sector. It follows that anomalies contribute to SUSY breaking in any case, irrespective of the main symmetry breaking mechanism. We shall refer to AMSB as the model in which all other components that mediate the SUSY breaking are suppressed and the anomaly mediation is the dominant mechanism. We study in detail the particle spectrum in anomaly mediated supersymmetry breaking models in which supersymmetry breaking terms are induced by the super-Weyl anomaly. We investigate the minimal anomaly mediated supersymmetry breaking models, gaugino assisted supersymmetry breaking models, as well as models with additional nondecoupling D-term contributions due to an extra gauge symmetry at a high energy scale.

1 Introduction

There are several theoretical motivations for believing that Supersymmetry, a symmetry between fermionic and bosonic degrees of freedom, may be an actual symmetry of nature. One reason, in particular, is that in the Standard Model (SM), the instability of elementary scalar fields to radiative corrections leads to the well known fine-tuning problem. Supersymmetry (SUSY) provides the only known framework that allows for the introduction of elementary scalar fields, essential for the breaking of electroweak symmetry, into the theory, without the need for fine tuning parameters to uncanny accuracy. This, requires that the SUSY breaking scale is $\mathcal{O}(1\text{ TeV})$, so that the supersymmetric partners of known particles should be accessible at high energy hadron colliders. However, after many years of searching in collider experiments, no evidence was found for the existence of supersymmetric particles. The negative results of the searches constrains the spectrum of the SUSY particles and of the parameters of the model. The mechanism of SUSY breaking itself is unclear. In the gravity mediated scenario, SUSY is broken in a hidden sector and the breaking is transmitted gravitationally to the observable sector. This mechanism is elegant, since it only requires already existing fields and interactions, like gravity. It suffers, however, from the so called SUSY flavour problem, since it requires a large amount of fine tuning in the squark and slepton mass matriced to avoid unobserved large flavour-changing neutral current effects. To cope with the SUSY flavour problem, different SUSY breaking mechanisms have been proposed. In the Gauge Mediated SUSY Breaking (GMSB) scenario the breaking is transmitted via gauge forces. This model predicts a very characteristic mass spectrum, with a light gravitino as the lightest supersymmetric particle (LSP), and typically long-lived next-to-lightest supersymmetric particles (NLSP).

Conformal anomaly is a quantum phenomenon that breaks the conformal symmetry of the classical theory. Anomaly Mediated Supersymmetry Breaking (AMSB) is special type of gravity mediated supersymmetry breaking that results in supersymmetry breaking being communicated to the supersymmetric Standard Model through the conformal anomaly. The minimal AMSB is very predictive: all the low energy phenomenology can be derived by adding to the Standard Model (SM) only two extra parameters and one sign. Unfortunately, the minimal AMSB model would imply negative squared masses (tachyons) for the sleptons at the electroweak scale. One way of getting rid of tachyons is to suppose additional, non-anomaly, contributions to the SUSY breaking which can generate a positive contribution to the soft masses squared. There are a few string-motivated solutions that generate such a positive contribution without spoiling the renormalization group (RG) invariance of the soft terms. In most cases, such a contribution is universal for all sfermion masses and, in practice, it is enough to add just one extra parameter to the model. This arises, for instance, when the visible and the hidden sectors in separate branes that communicate only through gravity. There are other solutions that lead to flavour dependent mass terms. Such possibilities are less predictive, since the sfermion spectrum depends on more parameters, and they will not be investigated further in this paper. In the following, the minimal AMSB with a single, flavour independent, sfermion mass parameter will be considered, as implemented in version 7.75 of the program ISAJET. However, the characteristic gaugino spectrum of AMSB is the same even for models without such an universal sfermion mass term, and most of the

considerations that follow can be applied also to them. We examine the reach of the CERN LHC pp collider for supersymmetric models where the dominant contribution to soft SUSY breaking parameters arises from the superconformal anomaly. In the simplest viable anomaly mediated SUSY breaking model, tachyonic slepton squared masses are made positive by adding a universal contribution to all scalars. The presence of terminating tracks in a subset of signal events could serve to verify the presence of a long lived lightest chargino which is generic in the minimal AMSB model.

How does one make contact between the theoretical ideas of supersymmetry and gauge theories of quarks and leptons on the one hand, and the observation of real particles such as π's, K e's, μ's and γ's in complicated collider experiments on the other? A crucial bridge of this gap has been provided by the development of event generation and simulation programs such as SUSYGEN and ISAJET. Such programs merge perturbatively calculable hard scattering processes with approximate all-orders QCD corrections and non-perturbative models for the hadronization of quarks, gluons and beam fragments. Programs have been developed to simulate essentially all lowest order and some higher order SM processes along with a few processes arising from physics beyond the SM. The capacity to simulate production of supersymmetric particles, however, has been included only at an elementary level in some of the generators. Motivated by both theoretical as well as aesthetic considerations, we have made a concerted effort to include a more realistic simulation of supersymmetry in ISAJET, so that the experimental consequences of supersymmetry can be explicitly viewed in the environment of a collider detector.

2 Anomaly Mediated Supersymmetry Breaking

Vector boson fusion (VBF) at hadronic machines such as the Large Hadron Collider (LHC) at CERN has been suggested as a useful channel for studying the signal of the Higgs boson. Characteristic features of this mechanism are two highly energetic quark-jets, produced in the forward direction in opposite hemispheres and carrying a large invariant mass. The absence of colour exchange between the forward jets ensures a suppression of hadronic activities in the central region. Though it was originally proposed as a background-free signal of a heavy Higgs, the usefulness of the VBF channel in uncovering an intermediate mass Higgs has also been subsequently demonstrated. Encouraged by all this, one naturally wants to know whether the VBF channel can be used to unravel other aspects of the basic constituents of nature, especially those bearing the stamp of physics beyond the standard model of elementary particles.

While a multitude of signals for SUSY at the up and coming accelerators have been proposed, here we want to stress the utility of VBF processes to probe the non-strongly interacting sector of the SUSY standard model. We point out in particular that some of the SUSY theories of considerable current interest can be tested in this way, via signals where nothing excepting the forward-tagged jets are visible.

When R-parity defined as $R = (-1)^{3B+L+2S}$ is conserved, a conventional method of searching for charginos $\chi^{\pm}$ and neutralinos χ^0 at hadron colliders is their direct production. The most convenient channel is $p\bar{p}$ / pp ${}^\circ\chi_1^{\pm}$ χ_2^0 followed by the decays $\chi_1^{\pm}$ ${}^\circ\chi_1^0 l^{\pm}\nu_l(\bar{\nu}_l)$ and χ_2^0 ${}^\circ\chi_1^0 l^+ l^-$, where χ_1^0 is the lightest SUSY particle and hence is invisible. The effectiveness of the VBF technique has also been demonstrated by us in an

R-parity violating scenario where it is rather difficult to distinguish the final states obtained via $p\bar{p}$ / pp $^\circ\chi_1^\pm$ χ_2^0 against cascades coming from the strongly interacting sector. In VBF channel, charginos and neutralinos produced with the help of the W-boson, the Z-boson and the photon lead to signatures of such models in the form of dileptons in background-free environments.

We will consider two specific examples which are of interest for the present purpose. The first one of these is a theory with Anomaly Mediated Supersymmetry Breaking (AMSB) where $\chi_1^\pm$ χ_1^0 are both wino-like and therefore very closely degenerate. The second instance is that of a SUSY Grand Unified Theory (GUT) with $M_2 >> \mu$, where M_2 is the $SU(2)$ gaugino mass and μ, the Higgsino mass parameter occurring in the superpotential. In that case, χ_1^0, $\chi_1^\pm$ and χ_2^0 are all Higgsino-like and have small mass separations.

AMSB models attempt to link the SUSY breaking mechanism to scenarios with extra compactified dimensions. The SUSY breaking sector is confined to a 3-brane separated from the one on which the standard model fields reside. SUSY breaking is conveyed to the observable sector by a super-Weyl anomaly terms, the gaugino and scalar masses are given by:

$$\begin{aligned} M_i &= b_i \frac{g_i^2}{16\pi^2} m_{3/2} \\ M^2_{scalar} &= c^2 \frac{m_{3/2}^2}{(16\pi^2)^2} + m_0^2 \end{aligned} \qquad (1)$$

Here b_i's are coefficients occurring in the β-functions of the appropriate gauge couplings and c's are combinations of β-functions and anomalous dimensions (of gauge and Yukawa couplings). m_0 is a scalar mass parameter introduced to prevent sleptons from becoming tachyonic.

In terms of the gravitino mass $m_{3/2}$ (which is much larger than the gaugino and squark masses), the β functions for the gauge and Yukawa couplings g_a and Y_i, and the anomalous dimensions γ_i of the chiral superfields, the soft SUSY breaking terms are given by:

$$\begin{aligned} M_a &= \frac{\beta_{g_a}}{g_a} m_{3/2} \\ A_i &= \frac{\beta_{Y_i}}{Y_i} m_{3/2} \\ m_i^2 &= -\frac{1}{4}\left(\Sigma_a \frac{\partial\gamma_i}{\partial g_a}\beta_{g_a} + \Sigma_k \frac{\partial\gamma_i}{\partial Y_k}\beta_{Y_k}\right) m_{3/2}^2 \end{aligned} \qquad (2)$$

These equations are RG invariant and thus valid at any scale and make the model highly predictive. The additional parameters, μ^2 and B are obtained as usual by requiring the correct breaking of the electroweak symmetry. One then has, in principle, only three input parameters $m_{3/2}, \tan\beta$ and sign(μ). However, this rather simple picture is spoiled by the fact that the anomaly mediated contribution to the slepton scalar masses squared is negative and the sleptons are in general tachyonic. This problem can be cured by adding a positive non–anomaly mediated contribution to the soft masses. The simplest phenomenological way of parameterizing the non–anomaly contribution is to

add a common mass parameter m_0 at the GUT scale, which would be then an additional input parameter to all the (squared) scalar masses. However in the general case, the non–anomaly mediated contribution might be different for different scalar masses and depend on the specific model which has been chosen. One should then write a general non–anomalous contribution at the GUT scale for each scalar mass squared:

$$m_{\tilde{S}_i}^2 = c_{S_i} m_0^2 - \frac{1}{4}\left(\Sigma_a \frac{\partial \gamma_i}{\partial g_a}\beta_{g_a} + \Sigma_k \frac{\partial \gamma_i}{\partial Y_k}\beta_{Y_k}\right) m_{3/2}^2 + \mathrm{D\,terms} \tag{3}$$

where the coefficients c_{S_i} depend on the considered model.

The prediction in AMSB of a wino-like LSP has interesting phenomenological consequences. The most striking of these is that the lightest chargino is nearly mass-degenerate with the lightest neutralino. Near-degenerate particles are not unusual in SUSY phenomenology, but with AMSB one of these particles is the LSP. In the MSSM there are two sources of anomalies: the ones due to quarks and leptons, and the ones due to the fermionic partners of the Higgs bosons, the higgsinos, which cancel separately to make the model anomaly-free. In fact, the higgsinos are not mass eigenstates, they mix with the superpartners of the gauge bosons (gauginos), and the resulting charged and neutral eigenstates are known as chargino and neutralino, respectively. Gauginos do not contribute to the anomaly because their couplings to the gauge bosons are vectorial. Although the MSSM is anomaly-free, it is relevant to understand the conditions under which charginos and neutralinos participate in the cancellation of anomalies, since this can play an important role for their decoupling. For instance, if it were possible for a heavy higgsino to contribute to the anomaly, the cancellation of anomalies would take place between different scales.

In order to identify the origin of anomalies we shall work with 4-component spinors for the gaugino and higgsino fields, however, the analysis of the large-μ limit and the calculations of interest will be performed in the mass-eigenstate basis, namely in terms of charginos and neutralinos. We shall review first the lagrangian of the model, focusing mainly in the interaction of the gauge bosons $(A_\mu, W^\pm_\mu, Z_\mu)$, with the charged $\tilde{H}$ and neutral $(\tilde{H}_1, \tilde{H}_2)$ higgsinos, and with the wino $\tilde{W}$, photino $\tilde{A}$ and zino $\tilde{Z}$ fields.

The lagrangian for the mass and mixing terms of gauginos and higgsinos in the MSSM is given by:

$$\begin{aligned}
\mathcal{L} \;=\;& M_{\tilde{W}} \bar{\tilde{W}}\tilde{W} + \frac{M_{\tilde{A}}}{2}\bar{\tilde{A}}\tilde{A} + \frac{M_{\tilde{Z}}}{2}\bar{\tilde{Z}}\tilde{Z} + \mu \bar{\tilde{H}}\tilde{H} \\
&+ \frac{M_{\tilde{Z}} - M_{\tilde{A}}}{2}\tan 2\theta_W \bar{\tilde{A}}\tilde{Z} - \frac{\mu}{2}[\bar{\tilde{H}}_1\tilde{H}_2 + \bar{\tilde{H}}_2\tilde{H}_1] \\
&- \frac{g}{\sqrt{2}}[\bar{\tilde{Z}} P_R \tilde{H}_1 H_1^1 - \bar{\tilde{H}}_2 P_R \tilde{Z} H_2^2 + h.c.] \\
&- g[\bar{\tilde{W}} P_R \tilde{H} H_1^1 + \bar{\tilde{H}} P_R \tilde{W} H_2^2 + h.c.]
\end{aligned} \tag{4}$$

which includes the interaction of gauginos and higgsinos with the neutral components of the scalar Higgs doublets (H_1^1, H_2^2). The zino and photino masses can be expressed in terms of the soft-breaking masses M and M', as follows: $M_{\tilde{Z}} = M\cos^2\theta_W + M'\sin^2\theta_W$, $M_{\tilde{A}} = M\sin^2\theta_W + M'\cos^2\theta_W$.

After SSB the Higgs scalars acquire vacuum expectation values (VEV's) $< H_1^1 >= v_1$ and $< H_2^2 >= v_2$, and the trilinear terms generate a mixing among the gauginos and

higgsinos. The resulting mass-mixing matrices need to be diagonalized. The mass-eigenstates and the diagonalizing matrices depend in general on the parameters M, M', μ and $\tan\beta$. The charginos and neutralinos are denoted by: $\tilde{\chi}_i^+$ $(i = 1, 2)$ and $\tilde{\chi}_j^0$ $(j = 1, 2, 3, 4)$, respectively.

The interaction of gauginos and higgsinos with the gauge bosons of the model are described by the lagrangian:

$$\begin{aligned}
\mathcal{L} &= e[\bar{\tilde{W}}\gamma_\mu \tilde{W} + \bar{\tilde{H}}\gamma_\mu \tilde{H}]A^\mu - e[\bar{\tilde{A}}\gamma^\mu \tilde{W} W_\mu^+ + \bar{\tilde{W}}\gamma^\mu \tilde{A} W_\mu^-] \\
&\quad - g\cos\theta_W[\bar{\tilde{Z}}\gamma^\mu \tilde{W} W_\mu^- + \bar{\tilde{W}}\gamma^\mu \tilde{Z} W_\mu^+ - \bar{\tilde{W}}\gamma_\mu \tilde{W} Z^\mu] \\
&\quad + \frac{g}{2cos\theta_W}[\cos 2\theta_W \bar{\tilde{H}}\gamma_\mu \tilde{H} - \frac{1}{2}(\bar{\tilde{H}}_1\gamma_\mu\gamma_5\tilde{H}_1 - \bar{\tilde{H}}_2\gamma_\mu\gamma_5\tilde{H}_2)]Z^\mu
\end{aligned} \tag{5}$$

We can discuss now the origin of anomalies in the higgsino sector. Before SSB the charged higssino couplings to the neutral gauge bosons are of vector type, and at this stage it does not contribute to the gauge anomaly. However, after SSB the mixing treats in a different way the L- and R-handed components of the charged higgsinos and winos, which induces an axial-vector part for their couplings, then each chargino contributes to the anomaly, but with opposite signs for the MSSM to remain anomaly-free. However, the coupling becomes again vector-like for $\tan\beta = 1$. On the other hand, the neutral higgsinos contribute to the anomaly, because their couplings have an axial-vector part even before SSB. However, these axial-vector couplings also vanish in the large μ limit.

The two doublet Higgs superfields H_1 and H_2 introduced previously are precisely those needed to generate quark and lepton masses in supersymmetric extensions of the standard model. The correspondance between our earlier notations for doublet Higgs superfields and mixing angle, and modern ones, is as follows:

$$\mathcal{W} \;=\; h_e\, H_1 \,.\, \bar{E}\, L \;+\; h_d\, H_1 \,.\, \bar{D}\, Q \;-\; h_u\, H_2 \,.\, \bar{U}\, Q \tag{6}$$

Here L and Q denote the left-handed doublet lepton and quark superfields, and $\bar{E}$, $\bar{D}$ and $\bar{U}$ left-handed singlet antilepton and antiquark superfields. The vacuum expectation values of the two Higgs doublets described by H_1 and H_2 generate charged-lepton and down-quark masses, and up-quark masses, given by $m_e = h_e\, v_1/2\,,\ m_d = h_d\, v_1/2\,,$ and $m_u = h_u\, v_2/2\,$, respectively.

The $SU(3)\times SU(2)\times U(1)$ gauge interactions of the chiral quark and lepton superfields, and of the two doublet Higgs superfields H_1 and H_2, are indeed invariant under this continous $U(1)$ R-symmetry. So are the super-Yukawa interactions of the two doublet Higgs superfields H_1 and H_2 responsible for the generation of quark and lepton masses through the superpotential. Indeed this trilinear superpotential transforms under continuous R-symmetry, according to

$$\mathcal{W}\,(\,x,\,\theta\,) \;\;\rightarrow\;\; e^{2\,i\alpha}\;\; \mathcal{W}\,(\,x,\,\theta\, e^{-i\alpha}\,)\;\; . \tag{7}$$

Its auxiliary "F-component" is therefore R-invariant and generates R-invariant interaction terms in the Lagrangian density.

AMSB has many attractive features: a large number of predictions, few parameters, an insensitivity to the UV and a mathematical framework that elegantly describes its affects. The latter property allows one to express the SUSY breaking effects by analytically continuing parameters into superspace. AMSB then gives a method or set of rules

on how to "promote" these parameters to superfields. To establish these rules, as well as get the basic concepts of AMSB we start with a generic SUSY theory given by the lagrangian:

$$\mathcal{L} = \frac{1}{2}\int d^4\theta \mathcal{K}(D_\alpha, Q, W_\alpha) + \int d^2\theta \mathcal{W}(Q, W_\alpha) + \text{h.c.} \tag{8}$$

where Q collectively represents the matter content and W_α is the gauge content– the dependence of $\mathcal{K}$ on $\bar{D}_{\dot{\alpha}}$, $Q^\dagger$, has been suppressed. AMSB then requires that $\mathcal{K}$ and $\mathcal{W}$ superconformal. To do this it is necessary to introduce the superconformal compensator ϕ which is an unphysical chiral multiplet with a weyl weight $d_W(\phi) = +1$ and an R charge of $+2/3$. The superconformal invariance then dictates the ϕ couplings so that the resulting theory is invariant under weyl scale transformations and $U(1)_R$. To see the required form for the ϕ coupling, we first note that the superspace coordinate charge assignments force the Kähler potential and Superpotential. If we take $d_W(\tilde{Q}) = d_W(\tilde{W}_\alpha) = R(\tilde{Q}) = R(\tilde{W}_\alpha) = 0$ with $\tilde{Q}$ being the matter fields and $\tilde{W}_\alpha$ the gauge fields, but not in the canonically normalized form, then we may write

$$\mathcal{W} = \widetilde{\mathcal{W}} X_{\mathcal{W}} \qquad\qquad \mathcal{K} = \widetilde{\mathcal{K}} X_{\mathcal{K}} \tag{9}$$

where the "tilded" potentials are functions of only the "tilded" fields. Since the "tilded" fields have no charges, hence all the transformational weights belong to the X_n:

$$\begin{aligned} d_W(X_{\mathcal{K}}) &= 2 & \qquad d_W(X_{\mathcal{W}}) &= 3 \\ R(X_{\mathcal{K}}) &= 0 & \qquad R(X_{\mathcal{W}}) &= 2 \end{aligned}$$

Now because the X_n carry charges, they can only depend on the conformal compensator ϕ. Therefore invariance necessitates

$$X_{\mathcal{K}} = \phi^\dagger \phi \qquad\qquad X_{\mathcal{W}} = \phi^3 \tag{10}$$

We can now write the most general superconformal invariant lagrangian. It is given by

$$\mathcal{L} = \frac{1}{2}\int d^4\theta X_{\mathcal{K}} \widetilde{\mathcal{K}}(\tilde{D}_\alpha, \tilde{Q}, \tilde{W}_\alpha) + \int d^2\theta X_{\mathcal{W}} \widetilde{\mathcal{W}}(\tilde{Q}, \tilde{W}_\alpha) + \text{h.c.} \tag{11}$$

This picture explicitly demonstrates the ϕ couplings as required by superconformal invariance at a cost of using non-canonically normalized fields. It is possible to return to the usual fields by defining

$$Q = \phi\tilde{Q} \qquad\qquad D_\alpha = \frac{\phi^\dagger}{\phi^{1/2}}\tilde{D}_\alpha \qquad\qquad W_\alpha = \phi^{3/2}\tilde{W}_\alpha \tag{12}$$

When including quantum corrections a mass parameter, μ, will be introduced upon which the couplings depend. The mass parameter will also require some type of regulator which can be chosen to be a cutoff Λ. This regulator is convenient to use because we have already established that such a cutoff must be paired with ϕ should it give rise to nonrenormalizable terms of the form in general canonical lagrangian. Thus, because it is necessary for μ to always appear in the ratio μ/Λ, the effect of μ is to promote the renormalized parameters to superfields through the rule

$$\mu \to \frac{\mu}{\sqrt{X_{\mathcal{K}}}} \tag{13}$$

The promotion of $Z(\mu)$ to a superfield $\mathcal{Z}(\mu)$ and $1/g^2(\mu)$ to the superfield $\mathcal{R}(\mu)$ gives rise to soft SUSY breaking terms. To obtain an expression for those terms it is convenient to chose a gauge where

$$\phi = 1 + F_\phi \theta^2 \tag{14}$$

To illustrate the UV insensitivity of AMSB, consider a threshold $\Lambda \gg M \gg F_\phi$ such a scale may be an explicit mass term in the superpotential or the vev of the scalar component of the superfield X. In either case we assume that below M there are no remnant singlets in the effective theory. This is the same as requiring that as $\Lambda \to \infty$, M remains finite. The previous condition ensures that the effective theory's lagrangian has the schematic form

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_Q + M^{-n} f(Q, \psi_Q) + M^4{}_Q + M^4 + \int d^2\theta \frac{Q^4}{M\phi} + \frac{Q^5}{M^2\phi^2} + \ldots + \text{h.c.} \tag{15}$$

where $n > 0$ and $\mathcal{L}_Q$ represents the part of the lagrangian involving only the various components of the matter superfields Q. This form of the effective theory makes explicit that the additional SUSY breaking effects from the threshold M go as $F_\phi/M \ll 1$. Thus, the rule $\mu \to \mu/\phi$ completely parameterizes all the SUSY breaking in both the high-scale and low-scale theories resulting in the maintenance of the AMSB.

3 SUSYGEN 3.0

SUSYGEN is a Monte Carlo program designed for computing distributions and generating events for MSSM sparticle production in pp, $\bar{p}p$ and e^+e^- collisions. The Supersymmetric mass spectrum may either be supplied by the user, or can alternatively be calculated in two different models of SUSY Breaking: gravity mediated supersymmetry breaking (SUGRA) and gauge mediated supersymmetry breaking (GMSB). The program incorporates the most important production processes and decay modes, including the full set of R-parity violating decays, and the decays to the gravitino in GMSB models. Initial state radiation corrections take into account p_T/p_L effects in the Structure Function formalism, and an optimised hadronisation interface to `JETSET` 7.4 including final state radiation is also provided.

This section provides an overview of the physics content of the generator. The implemented SUSY production mechanisms are described, and the sparticle decays. The diagrams for the s- and t-channel production of charginos and neutralinos SUSYGEN processes are shown. For large sneutrino and slepton masses the s-channel diagram dominates, while for small sneutrino (slepton) masses the t-channel contributions can be large, resulting in constructive interference for chargino (neutralino) production. The cross sections therefore depend on the chargino and neutralino masses and their couplings. Sfermions are produced in pairs through γ, Z exchange in the s-channel. The *snue* and *sel* are also produced with chargino and neutralino exchange in the t-channel. The sfermion cross sections depend on the sfermion masses, and on the chargino or the neutralino masses and couplings in the case of electron-sneutrino and selectron pair production, respectively. For the third generation sfermions $\tilde{\tau}$, $\tilde{t}$ and $\tilde{b}$ the left and right sfermion states can mix, and the cross sections also depend on the mixing angle $\theta_{\tilde{f}}$. Finally the Higgs production processes hZ, HZ, hA, HA, H^+H^- are also provided through

an interface to PYTHIA. This is the less developed part of the program, and we suggest that more specialised programs are used for dedicated Higgs studies. Sparticles can decay in two modes. In the conserving mode sparticles decay to lighter sparticles and SM particles. In the violating mode sparticles can additionally decay to SM particles only.

The charginos χ_n^+ and the higher mass neutralinos $\tilde{\chi}_k^0$ can decay to the three-body final states. One can in general distinguish between two regimes: In the first the scalar masses are much larger than the gaugino mass, and the decays occur through the s-channel to off-shell gauge bosons and the lighter gauginos, the $W^*\chi^0$, $Z^*\chi^+$ channels in the case of the chargino decays and the $W^*\chi^+$, $Z^*\chi^0$ in the case of the destructive neutralino decays. In this case the different branching ratios are mostly determined from the decays of the off-shell W^* and Z^*. In the second regime the sfermions have masses close to or below the gauginos, and the u,t-channels with $\tilde{l}^*$, $\tilde{\nu}^*$ or $\tilde{q}^*$ exchange dominate and enhance the branching ratios to the corresponding fermions. Particular care has been taken to take into account the masses of the final fermions, so that scenarios where one has chargino and neutralino masses. If the sfermion mass is below the gaugino mass, two-body decays of the gauginos to the sfermions become dominant decay modes. Instead the three-body calculation is used, and the pole at $p^2_{\tilde{f}} = M^2_{\tilde{f}}$ is avoided by the inclusion of the sfermion width in the propagator. The propagator term $D = (p^2_{\tilde{f}} - M^2_{\tilde{f}})^{-1}$ is replaced by $D = (p^2_{\tilde{f}} - M^2_{\tilde{f}} + iG_{\tilde{f}})^{-1}$, where $G_{\tilde{f}} = \Gamma_{\tilde{f}} M_{\tilde{f}}$. Above threshold the propagator term forces the two-body kinematics, and the three-body decay is therefore equivalent to two two-body decays. In addition to the decay modes the gauginos can either decay to the Higgs, or in restricted regions of parameter space radiatively via one loop diagrams.

In GMSB models the gravitino is the LSP. The coupling of the gravitino can be very small, and thus the decay $\chi_1^0 \to \tilde{G}\gamma$ is phenomenologically the most interesting mode if it occurs inside the detector. The sfermion decays to a gaugino and a fermion can also be separated into two cases. In the first case the lightest neutralino χ_1^0 is the only gaugino lighter than the sfermion, with the exception of the stop. In the second case heavier neutralinos χ_k^0 or charginos χ_n^+ may be lighter than the sfermion, and the sfermion decays through a cascade of gauginos. In GMSB models decays to gravitinos are also possible, although in practice only the decay of the NLSP to the gravitino is of importance. The above decays cover neutralino and gravitino LSP scenarios. If the sneutrino is the LSP, sleptons and squarks can also decay via virtual W^*, Z^*, χ^{+*} and χ^{0*} exchange to the sneutrino. SUSYGEN implements decays for a single non-zero R-parity violating coupling $\lambda_{ijk}, \lambda'_{ijk}$ or λ''_{ijk}, where i, j, k are generation indices, and the three couplings correspond to the $LL\bar{E}$, $LQ\bar{D}$ or $\bar{U}\bar{D}\bar{D}$ operators. Neutralinos can decay and show the corresponding diagrams for the $LQ\bar{D}$ operator.

The above decays are particularly relevant when the chargino is the LSP. Charginos will normally decay to the neutralino if the neutralino is the LSP, in which case the decays only dominate for large couplings λ and when the exchanged sfermion mass is close to the mass of the chargino. Sfermions can decay directly to SM particles through a dominant $LL\bar{E}$ coupling. For a dominant $LQ\bar{D}$ operator sfermions decay and similarly for a dominant $\bar{U}\bar{D}\bar{D}$ operator. These decays are only of importance if the produced sfermion is the NLSP which cannot decay directly via a specific violating coupling, and the LSP is another sfermion. Final state radiative corrections are implemented within SUSYGEN. QED and QCD corrections to quark final states are treated by JETSET in the hadronisation interface.

The generator calculates the lifetime of the sparticles from their decay rate, and implements secondary vertices for long-lived sparticles accordingly. The lifetime information is important for the violating LSP decays when the coupling strength λ is small, and for the GMSB decays to the gravitino. The inclusion of lifetime effects can be optionally turned off.

SUSYGEN is fully interfaced to JETSET 7.4 which takes care of the hadronisation of quarks. In the independent fragmentation (IF) scheme the final state quarks are treated as independent particles with respect to each other. There is no QCD radiation between the final state quarks, and the hadronisation process produces relatively hard jets. Clearly this is an unphysical simplification, and the IF scheme should only be used to compare and evaluate the effect of gluon radiation. The jets are much softer owing to the gluon radiation between the quark states, which produces additional soft particles. In the simplest case when there are only two final state quarks there is no ambiguity in the colour string assignment. In the case when quarks are produced by colourless sparticles a colour string is formed between each of the decay products of the colourless states. At present the JETSET hadronisation interface described above has two limitations. Firstly if squarks decay via the violating coupling λ'' to two quarks $\tilde{q}_1 \to q_2 q_3$ the colour string connection between $q_2 q_3$ is not supported by JETSET, and we have to resort to the independent fragmentation scheme instead. Secondly, because the lifetime of the decay $\tilde{t}\chi^0 c$ is larger than the hadronisation scale, stops should hadronise prior to their decay. Stop meson hadronisation is not implemented in SUSYGEN.

In SUSYGEN , the spectrum calcutation in AMSB models is performed via an interface to the `SuSpect` program. `SuSpect`, in its latest version 2.3 that we present here, is a FORTRAN code which calculates the supersymmetric and Higgs particle spectrum in the constrained and unconstrained MSSMs. At the present stage, it deals with the phenomenological MSSM with 22 free parameters defined either at a low or high energy scale, with the possibility of RG evolution to arbitrary scales, and the most studied constrained models, namely mSUGRA, AMSB and GMSB. Many intermediate models are easily handled. The program includes the three major ingredients which should be incorporated in any algorithm for the constrained MSSMs: renormalization group evolution of parameters between a low energy scale and a high energy scale. Consistent implementation of radiative electroweak symmetry breaking (EWSB), calculation of the physical masses of the superparticles and Higgs bosons, including all relevant features such as the mixing between various states and the radiative corrections. The program is simple to use, self–contained and can easily be linked to other codes.

4 ISAJET 7.75

ISAJET is a Monte Carlo program which simulates pp, $p\bar{p}$ and to a lesser extent e^+e^- interactions at high energy. Much of the simulation is based on perturbative QCD plus phenomenological models for parton and beam jet evolution. Events are generated in four distinct steps: A primary hard scattering is generated according to the appropriate QCD cross section. QCD radiative corrections are added for both the initial and the final state. Beam jets are added assuming that these are identical to a minimum bias event at the remaining energy.

ISAJET is supported for ANSI Fortran and for Cray, DEC Ultrix, DEC VMS,

HP/9000 7xx, IBM VM/CMS 370 and 30xx, IBM AIX RS/6000, Linux, Silicon Graphics 4D, and Sun computers. The CDC 7600 and ETA 10 versions are obsolete and are no longer supported. It is written mainly in ANSI standard FORTRAN 77, but it does contain some extensions except in the ANSI version. The code is maintained with a combination of RCS, the Revision Control System, and the Patchy code management system, which is part of the CERN Library.

ISAJET incorporates ISASUSY, which evaluates branching ratios for the minimal supersymmetric extension of the standard model.

Event simulation is carried out by the following steps:

- calculation of hard scattering subprocess Feynman diagrams,
- convolution with Q^2 dependent parton distribution functions,
- implementation of approximate all orders QCD corrections via final and initial state parton showers,
- implementation of predicted particle and sparticle decays, along with parton radiation and independent quark and gluon hadronization,
- suitable modelling of the underlying event structure and beam jet evolution.

To incorporate supersymmetric processes into ISAJET, the appropriate sparticle subprocess production cross-sections and the corresponding sparticle decay modes as predicted within the MSSM framework are needed. Both production and decay processes depend in general on the parameter set m, m, μ, $\tan\beta$, m_{H_p}, and m_t. Other elements of the simulation are essentially unchanged. The complete spectrum of MSSM sparticle states have been defined within ISAJET, with accompanying identification codes. The supersymmetric particle IDENT codes distinguish between the partners of left and right handed fermions and include the Higgs sector of the minimal supersymmetric model.

ISAJET contains sufficient flexibility that some scenarios for non-minimal SUSY can also be studied. For instance, R-violating models with an unstable $_1$ can be easily simulated by using the ISAJET `FORCE` keyword command to force the desired $_1$ decay. `FORCE` can also be used to override ISASUSY generated decays, or to select specific decay modes for certain sparticles. In addition, the unification condition on gaugino masses can be relaxed if desired. This can be done by a simple modification of the FORTRAN code in subroutine SSMASS. Some modifications, such as added Higgs singlets which can also enlarge the neutralino sector, are more difficult to include, and would require a more substantial code revision.

The generator can also be used to simulate top squark events even before stops are officially included. For instance, by setting the `JETTYPEi` to be bottom squarks, one generates nearly the same cross-section as for top squarks. Then the user may use the `FORCE` command to force the generated squarks to decay into the desired modes.

There are still many aspects of MSSM sparticle production that are not included in the current version of ISAJET, but will hopefully be included in future versions. A partial list includes the following:

- top squark production and decay,

- slepton pair production processes,
- a subroutine to notify if the parameters are in violation of LEP limits,
- direct MSSM Higgs boson production mechanisms,
- neutralino pair production processes,
- Higgs decays to sfermion pairs,
- further breaking of sfermion degeneracies, especially for the third generation,
- improved calculations of radiative corrections to the Higgs sector,
- e^+e^- production of SUSY particles.

ISASUSY a subset of ISAJET 7.75 is used to calculate sparticle masses, mixings and branching fractions. is automatically called by ISAJET whenever the `MSSM1` and `MSSM2` keywords are used. In this case, ISASUSY fills an internal ISAJET decay table with the appropriate decay modes and branching fractions; the modes themselves are not printed since output consists of many pages. The user may however run ISASUSY as a separate package to generate a file of all calculated masses and decay modes, partial widths and branching fractions.

Compiling and linking are straightforward, since ISASUSY doesn't need to be linked with any other files.

When running ISASUSY, the program will ask for an output filename in single quotes. After entering, ISASUSY asks for the same parameter set as ISAJET: m, m, $m_{_L}$, $m_{_R}$, $m_{_L}$, $m_{_R}$, $m_{_L}$, $\tan\beta$, m_{H_p}, μ, m_t. Output will then be written to the specified file for viewing or printing.

It should be noted that some choices of parameters will result in $m_{_1} < m_{_1}$, violating the assumption that $_1$ is the LSP. In this case, ISASUSY replies with a warning, and terminates execution. Other choices of parameters can be in regions already excluded by LEP constraints. At present, no warnings are issued for this case.

In addition to the event generator, `isajet.car` contains two programs to calculate SUSY masses and decay modes: ISASUSY, which accepts weak scale parameters, and ISASUGRA, which calculates the weak scale parameters from those at some high scale. The main programs, SSRUN and SUGRUN respectively, are included. They both prompt for interactive input and then call the appropriate ISAJET subroutines. The output is formatted and printed by SSPRT and SUGPRT respectively. Executables for ISASUSY and ISASUGRA are built by the Unix `Makefile` and VMS `isamake.com`.

It is fairly straightforward to modify these routines to scan SUSY parameters, but given the variety of possible scans, no attempt has been made to provide code for this. If only masses are needed, SSMSSM can be modified to remove the calls to the routines that calculate branching ratios.

`IsaTools` is a optional set of subroutines included with Isajet 7.72 and later for the evaluation of various low-energy and cosmological constraints on supersymmetric models using the Isajet supersymmetry code. The package consists of:

1. `IsaRED`: subroutines to evaluate the relic density of (stable) neutralino dark matter in the universe,

2. `IsaBSG`: subroutines to evalue the branching fraction $BF(b \to s\gamma)$,
3. `IsaAMU`: subroutines to evaluate supersymmetric contributions to $\Delta a_\mu = (g-2)_\mu/2$,
4. `IsaBMM`: subroutines to evaluate $BF(B_s \to \mu^+\mu^-)$ and $BF(B_d \to \tau^+\tau^-)$ in the MSSM,
5. `IsaRES`: subroutines to evaluate the spin-independent and spin-dependent neutralino-proton and neutralino-neutron scattering cross sections for direct detection of dark matter.

Below we provide a brief description of each subroutine along with appropriate references. The main code author is indicated by an underline and should be the first choice of contact for any bug related problems.

`IsaRED` evaluates the neutralino relic density in the MSSM. The complete set of tree-level annihilation and co-annihilation processes is evaluated. Calculations are based on the matrix element library created using the CompHEP program and interfaced to Isajet. The following SUSY particles in the initial state are taken into account: $\tilde{e_1}$, $\tilde{\mu_1}$, $\tilde{\tau_1}$, $\tilde{\nu_e}$, $\tilde{\nu_\mu}$, $\tilde{\nu_\tau}$, $\tilde{u_1}$, $\tilde{d_1}$, $\tilde{c_1}$, $\tilde{s_1}$, $\tilde{t_1}$, $\tilde{b_1}$, $\tilde{g}$.

The subroutine `IsaBSG` evaluates the $BF(b \to s\gamma)$ using the effective field theory approach of Anlauf, wherein the Wilson coefficients of various operators are calculated at the relevant scales where various sparticles are integrated out of the theory. This method is used to handle the tW, tH^- and loops. The Wilson coefficients are evolved to scale $Q = M_W$, wherein the effective theory is taken to be the SM. The SM Wilson coefficients are evolved to $Q = m_b$ using NLO anomalous dimension matrices. Once at scale $Q = m_b$, the complete NLO corrections to the O_2, O_7 and O_8 operators are included. The scale dependence of the final result is of order 10%. In the high scale calculation, the weak scale value of $m_b(M_{SUSY})$ is calculated using two loop RG evolution with full one loop corrections to m_b. This effect is important at large $\tan\beta$. Also, the loops are included directly at scale $Q = M_W$. This necessitates an RG computation of well over 100 soft terms and couplings in order to generate the proper off diagonal soft terms at scale $Q = M_W$.

`IsaAMU` Supersymmetric contributions to $a_\mu = (g-2)_\mu/2$ come from the loops.

`IsaBMM` This subroutine evaluates the branching ratio of the decays $B_s \to \mu^+\mu^-$ and $B_d \to \tau^+\tau^-$. The effective Hamiltonian contain the Higgs-mediated flavor changing neutral currents that arise as a consequence of coupling of Higgs superfield $\hat{h}_u$ with down type fermions at one-loop level. Since this coupling is enhanced for large $\langle h_u\rangle/\langle h_d\rangle \equiv \tan\beta$, the calculations were performed keeping only terms that are most enhanced by powers of $\tan\beta$. Moreover, in the calculations of one-loop vertex corrections, it has been assumed that the chargino masses are well approximated by $|M_2|$ and $|\mu|$.

`IsaRES` evaluates the spin-independent and spin-dependent neutralino-proton and neutralino-neutron scattering cross sections.

The interactions for elastic scattering of neutralinos on nuclei can be described by the sum of spin-independent $\mathcal{L}^{eff}_{scalar}$ and spin-dependent $\mathcal{L}^{eff}_{spin}$ Lagrangian terms:

$$\mathcal{L}^{eff}_{elastic} = \mathcal{L}^{eff}_{scalar} + \mathcal{L}^{eff}_{spin}. \tag{15}$$

σ_{SI} for neutralino scattering off of nuclei is the main experimental observable since σ_{SI} contributions from individual nucleons in the nucleus add coherently and can be

expressed via SI nuclear form-factors. The cross section σ_{SI} receives contributions from neutralino-quark interactions via squark, Z and Higgs boson exchanges, and from neutralino-gluon interactions involving quarks, squarks and Higgs bosons at the 1-loop level. The differential σ_{SI} off a nucleus X_Z^A with mass m_A takes the form

$$\frac{d\sigma^{SI}}{d|\vec{q}|^2} = \frac{1}{\pi v^2}[Zf_p + (A-Z)f_n]^2 F^2(Q_r), \tag{15}$$

where $\vec{q} = \frac{m_A m_{\tilde{Z}_1}}{m_A + m_{\tilde{Z}_1}} \vec{v}$ is the three-momentum transfer, $Q_r = \frac{|\vec{q}|^2}{2m_A}$ and $F^2(Q_r)$ is the scalar nuclear form factor, $\vec{v}$ is the velocity of the incident neutralino, f_p and f_n are effective neutralino couplings to protons and neutrons respectively. The original calculation can be expressed as

$$\frac{f_N}{m_N} = \sum_{q=u,d,s} \frac{f_{Tq}^{(N)}}{m_q} \left[f_q^{()} + f_q^{(H)} - \frac{1}{2} m_q m_1 g_q \right] + \frac{2}{27} f_{TG}^{(N)} \sum_{c,b,t} \frac{f_q^{(H)}}{m_q} + \cdots \tag{15}$$

where $N = p,\ n$ for neutron, proton respectively, and $f_{TG}^{(N)} = 1 - \sum_{q=u,d,s} f_{Tq}^{(N)}$. The expressions for the $f_q^{(H)}$ couplings as well as other terms denoted by $\cdots$ are omitted for the sake of brevity.

The parameters $f_{Tq}^{(p)}$, defined by

$$< N|m_q \bar{q} q|N >= m_N f_{Tq}^{(N)} \qquad (q = u, d, s) \tag{15}$$

contain uncertainties due to errors on the experimental measurements of quark masses.

The cross section σ_p^{SI} for neutralino scattering off the proton is calculated in the limit of zero momentum transfer

$$\sigma^{SI} = \frac{4}{\pi} m_r^{N^2} f_N^2 \tag{15}$$

where $m_r^N = m_N m_{\tilde{Z}_1}/(m_N + m_{\tilde{Z}_1})$.

In our calculations we are using the CTEQ5L set of parton density functions evaluated at the QCD scale $Q = \sqrt{M_{SUSY}^2 - m_{\tilde{Z}_1}^2}$. The PDF parton density function can be easily updated to any other PDF upon request.

`IsaTools` is so far interfaced only to ISASUGRA, not to ISAJET or ISASUSY. Since `IsaRED` contains about 1.4M lines of Fortran code generated by CompHEP, both compilation and execution are somewhat slow. It was therefore decided to make `IsaTools` optional and to keep this code in a separate file, `isared.tar`. The outputs from `IsaTools` will appear after the mass spectrum and before the list of decay modes.

5 SUSY Models

The 24 MSSMi parameters describe the MSSM at the weak scale with the additional assumptions of exact flavor and CP conservation; the general MSSM has 105 parameters. These weak-scale SUSY-breaking parameters presumably arise from spontaneous SUSY breaking in a hidden sector that is communicated to the MSSM at some scale $M \gg M_Z$. There are a number of plausible models in which this symmetry breaking is simple, so

that the MSSM at the high scale involves only a small number of parameters. These are then related to those at the weak scale by the renormalization group equations (RGE's).

Isajet therefore implements in subroutine SUGRA the complete 2-loop RGE's for the gauge couplings, Yukawa couplings, and soft breaking terms. Contributions from right-handed neutrinos are optionally included. The RGE's are solved iteratively, running from the weak scale to the high scale M and back using Runge-Kutta integration. After each iteration the SUSY masses are recalculated, and the renormalization group improved 1-loop corrected Higgs potential is calculated and minimized. These results are used to modify the RGE β-functions appropriately as each threshold is crossed during the next iteration. The whole process is repeated, increasing the number of Runge-Kutta steps by a factor of 1.2 for each iteration, until all the RGE variables except μ and B differ by less than 0.3%. Since μ and B vary rapidly near the weak scale, they are only required to differ by less than 5%. The requirement of good electroweak symmetry breaking, $\mu^2 > 0$, is only imposed after the iterative solution has converged.

A number of different models for SUSY breaking at the high scale are included in ISAJET. The `SUGRA` parameters must be specified for the minimal supergravity framework. This assumes that the gauge couplings unify at the GUT scale, $M \sim 10^{16}\,\mathrm{GeV}$, defined by $\alpha_2 = \alpha_1$. SUSY breaking occurs at that scale with universal soft breaking terms produced by gravitational interactions with a hidden sector. The parameters of the model are

- m_0: the common scalar mass at the GUT scale,
- $m_{1/2}$: the common gaugino mass at the GUT scale,
- A_0: the common soft trilinear SUSY breaking parameter at the GUT scale,
- $\tan\beta$: the ratio of Higgs vacuum expectation values at the electroweak scale,
- $\mathrm{sgn}\mu = \pm 1$: the sign of the Higgsino mass term.

An attractive feature of this model is that the Higgs are unified with the other scalars at the GUT scale but $m_{H_u}^2$ is driven negative by the large top Yukawa coupling f_t. Isajet imposes this radiative symmetry breaking for the SUGRA model but not other possible constraints such as b-τ unification or limits on proton decay.

The SUGRA model with exact compling constant unification produces too large a value of α_s at the weak scale. The default is to use the experimental value, assuming that threshold effects at the GUT scale produce this. Exact unification can also be imposed. The assumption of universality at the GUT scale is rather restrictive and may not be valid. A variety of non-universal SUGRA (NUSUGRA) models can be generated using the `NUSUG1`, ..., `NUSUG5` keywords. These might be used to study how well one could test the minimal SUGRA model. The keyword `SSBCSC` can be used to specify an alternative scale (not the coupling constant unification scale) for the RGE boundary conditions. A SUGRA model with non-universal Higgs masses m_{H_u} and m_{H_d} which are determined via input of weak scale parameters μ and m_A can be input using the `NUHM` keyword.

An alternative to the SUGRA model is the Gauge Mediated SUSY Breaking (GMSB) model of Dine, Nelson, and collaborators. In this model SUSY breaking is communicated through gauge interactions with messenger fields at a scale M_m small compared to the

Planck scale and are proportional to gauge couplings times Λ_m. Since M_m is small and the masses at it are the same for each generation, there are no flavor changing neutral currents. The messenger fields should form complete $SU(5)$ representations to preserve the unification of the coupling constants. The parameters of the GMSB model, which are specified by the `GMSB` keyword, are

- $\Lambda_m = F_m/M_m$: the scale of SUSY breaking, typically 10–100 TeV,
- $M_m > \Lambda_m$: the messenger mass scale,
- N_5: the equivalent number of $5 + \bar{5}$ messenger fields.
- $\tan\beta$: the ratio of Higgs vacuum expectation values at the electroweak scale,
- $\mathrm{sgn}\mu = \pm 1$: the sign of the Higgsino mass term,
- $C_{\mathrm{grav}} \geq 1$: the ratio of the gravitino mass to the value it would have had if the only SUSY breaking scale were F_m.

In GMSB models the lightest SUSY particle is always the nearly massless gravitino $\tilde{G}$. The parameter C_{grav} scales the gravitino mass and hence the lifetime of the next lightest SUSY particle to decay into it. The `NOGRAV` keyword can be used to turn off gravitino decays.

A variety of non-minimal GMSB models can be generated using additional parameters set with the GMSB2 keyword. These additional parameters are

- R, an extra factor multiplying the gaugino masses at the messenger scale. (Models with multiple spurions generally have $R < 1$.)
- $\delta M^2_{H_d}$, $\delta M^2_{H_u}$, Higgs mass-squared shifts relative to the minimal model at the messenger scale. (These might be expected in models which generate μ realistically.)
- $D_Y(M)$, a $U(1)_Y$ messenger scale mass-squared term (D-term) proportional to the hypercharge Y.
- N_{5_1}, N_{5_2}, and N_{5_3}, independent numbers of gauge group messengers. They can be non-integer in general.

Gravitino decays can be included in the general MSSM framework by specifying a gravitino mass with `MGVTNO`. The default is that such decays do not occur.

Another alternative SUSY model choice allowed is anomaly-mediated SUSY breaking, developed by Randall and Sundrum. In this model, it is assumed that SUSY breaking takes place in other dimensions, and SUSY breaking is communicated to the visible sector via the superconformal anomaly. In this model, the lightest SUSY particle is usually the neutralino which is nearly pure wino-like. The chargino is nearly mass degenerate with the lightest neutralino. It can be very long lived, or decay into a very soft pion plus missing energy. The model incorporated in ISAJET, based on work by Ghergetta, Giudice and Wells (hep-ph/9904378), and by Feng and Moroi (hep-ph/9907319) adds a universal contribution m_0^2 to all scalar masses to avoid problems with tachyonic scalars. The parameters of the model, which can be set via the `AMSB` keyword, are

- m_0: Common scalar mass,
- $m_{3/2}$: Gravitino mass, typically 10 TeV since $m_i = (\beta_i/g_i)m_{3/2}$.
- $\tan\beta$: Usual ratio of vev's at weak scale,
- sgnμ: Usual sign of μ, ± 1.

Care should be taken with the chargino decay, since it may have macroscopic decay lengths, or even decay outside the detector. A variety of non-minimal AMSB models can be generated by using the AMSB2 keyword, which allows input of c_f multipliers of the m_0^2 contribution to sfermion masses:

$$m_{\tilde{f}}^2 = m_{\tilde{f}}^2(AMSB) + c_f m_0^2, \tag{15}$$

for $f = Q, D, U, L, E, H_d$ and H_u.

The mixed modulus-AMSB model, inspired by the KKLT string model of compactification of type IIB strings with fluxes, is also available by stipulating the `MMAMSB` keyword. Inputs consist of the mixing parameter α, $m_{3/2}$, $\tan\beta$ and $sign(\mu)$. Also, the modular weights n_Q, n_D, n_U, n_L, n_E, n_{H_d}, n_{H_u} must be specified, as well as moduli powers ℓ_1, ℓ_2 and ℓ_3 in the gauge kinetic function. These latter quantities are usually all taken equal to 1 for gauge fields on a D7 brane. The matter and Higgs field modular weights can be 0, 1 or 1/2 depending on whether the fields live on a D7 or D3 brane, or their intersection. The mixing parameter $-20 < \alpha < 20$ while $m_{3/2} : 2 - 50$ TeV.

Since neutrinos seem to have mass, the effect of a massive right-handed neutrino has been included in ISAJET, when calculating the sparticle mass spectrum. If the keyword `SUGRHN` is used, then the user must input the 3rd generation neutrino mass (at scale M_Z) in units of GeV, and the intermediate scale right handed neutrino Majorana mass M_N, also in GeV. In addition, one must specify the soft SUSY-breaking masses A_n and $m_{\tilde{\nu}_R}$ valid at the GUT scale. Then the neutrino Yukawa coupling is computed in the simple see-saw model, and renormalization group evolution includes these effects between M_{GUT} and M_N. Finally, to facilitate modeling of $SO(10)$ SUSY-GUT models, loop corrections to 3rd generation fermion masses have been included in the ISAJET SUSY models.

The ISASUSY program can also be used independently of the rest of ISAJET, either to produce a listing of decays or in conjunction with another event generator. ISASUSY accepts soft SUSY breaking parameters at the weak scale and calculates the masses and decay modes from them. The ISASUGRA program can also be used independently to solve the renormalization group equations with SUGRA, NUSUGRA, GMSB, or AMSB boundary conditions and then to call ISASUSY to calculate the decay modes.

Generally the MSSM, SUGRA, or GMSB option should be used to study supersymmetry signatures, the SUGRA or GMSB parameter space is clearly more manageable. The more general option may be useful to study alternative SUSY models. It can also be used to generate pointlike color-3 leptoquarks in technicolor models by selecting squark production and setting the gluino mass to be very large. The MSSM or SUGRA option may also be used with top pair production to simulate top decays to SUSY particles.

6 Results

This scenario features a very small neutralino–chargino mass difference, which is typical for AMSB scenarios. Accordingly, the LSP is a neutral wino and the NLSP a nearly degenerate charged wino.

Point:

$$m_0 = 400\,\mathrm{GeV}, \quad m_{3/2} = 60\,\mathrm{TeV}, \quad \tan\beta = 30, \quad \mu > 0.$$

Slope:

$$m_0 = 0.0067\, m_{3/2}.$$

For mAMSB model we have:

$$c_Q = c_u = c_d = c_L = c_e = c_{Hu} = c_{Hd} = 1.$$

6.1 SUSYGEN

```
Inputs:

m0       =   400.000          tan(beta) =    30.000
m3/2     = 60000.000          mu/|mu|   =     1
cQ       =      1.            cuR       =     1.
cdR      =      1.
cL       =      1.            ceR       =     1.
cHu      =      1.            cHd       =     1.
Ecm      = 14000.000          Rad.Corr. =     0

 Sparticle masses

SUPR     1554.  SUPL      1560.
SDNR     1556.  SDNL      1566.
SELR      329.  SELL       332.
SNU       322.
STP1     1158.  STP2      1346. cosmix = -0.501
SBT1     1282.  SBT2      1409. cosmix =  0.956
STA1      109.  STA2       375. cosmix=   0.639
SGLU     1570.

M1 =    530.717 M2 =    169.746 M3 =  1569.748

NEUTRALINO m, CP, ph/zi/ha/hb 1 =  168.6  1. -0.478 -0.875  0.014  0.068
NEUTRALINO m, CP, ph/zi/ha/hb 2 =  529.7  1.  0.878 -0.476  0.023  0.045
NEUTRALINO m, CP, ph/zi/ha/hb 3 = 1193.8 -1.  0.004  0.044 -0.683  0.729
NEUTRALINO m, CP, ph/zi/ha/hb 4 = 1196.0  1.  0.015 -0.073 -0.730 -0.680

CHARGINO MASSES    =   168.601  1196.651
CHARGINO ETA      =    -1.000     1.000
```

```
 U matrix   WINO    HIGGSINO
W1SS+        -0.995     0.097
W2SS+         0.097     0.995

 V matrix   WINO    HIGGSINO
W1SS-         1.000    -0.017
W2SS-         0.017     1.000
```

6.2 ISAJET

```
Anomaly-mediated SUSY breaking model:

M_0,  M_(3/2),  tan(beta),  sgn(mu),  M_t =
  400.000 60000.000    30.000     1.0   175.000

ISASUGRA unification:
M_GUT      = 0.167E+17   g_GUT          =0.710      alpha_GUT =0.040
FT_GUT     = 0.554       FB_GUT         = 0.243     FL_GUT = 0.232

1/alpha_em =  127.84     sin**2(thetaw) =0.2309     a_s^DRB   =  0.119
M_1        =  552.60     M_2            =  166.09   M_3       =-1234.36
mu(Q)      =  977.94     B(Q)           =   12.33   Q         =  968.11
M_Hd^2     =-0.577E+06   M_Hu^2         =-0.948E+06 TANBQ     =  29.203

ISAJET masses (with signs):
M(GL)   =  1304.56
M(UL)   =  1283.52   M(UR)   =  1291.85   M(DL)   =  1286.18   M(DR) =  1302.87
M(B1)   =  1019.60   M(B2)   =  1127.65   M(T1)   =   936.08   M(T2) =  1095.99
M(SN)   =   308.07   M(EL)   =   320.39   M(ER)   =   302.78
M(NTAU)=   276.82   M(TAU1)=   132.05   M(TAU2)=   346.10
M(Z1)   =  -172.70   M(Z2)   =  -542.47   M(Z3)   =   977.61   M(Z4) =  -979.83
M(W1)   =  -172.88   M(W2)   =  -980.34
M(HL)   =   117.08   M(HH)   =   619.25   M(HA)   =   615.28   M(H+) =   625.39

theta_t=  -0.9706   theta_b=   0.4621   theta_l=   0.9278   alpha_h=  0.0366

NEUTRALINO MASSES (SIGNED) =   172.704   542.466  -977.605   979.833
EIGENVECTOR 1       =  -0.01699   0.08196   0.99649  -0.00335
EIGENVECTOR 2       =   0.03647  -0.06359   0.00921   0.99727
EIGENVECTOR 3       =   0.70752   0.70494  -0.04585   0.01950
EIGENVECTOR 4       =  -0.70555   0.70164  -0.06949   0.07118

CHARGINO MASSES (SIGNED)  =   172.876   980.340
GAMMAL, GAMMAR            =   1.68674   1.59556
```

6.3 Comparison of Populations

Evaluation of an n-dimensional integral over an interval divided into N subintervals requires N^n function evaluations. A statistical hypothesis is an assertion that a random variable has a particular probability distribution. For complex statistical testing the reader is referred to program packages such as in the CERN library. Testing an hypothesis involves calculating the probability that the random variable would deviate from the value predicted by the presumed underlying distribution. If the probability is less than some confidence level, the hypothesis is accepted. If the calculated probability exceeds the confidence level, the hypothesis is rejected. A common hypothesis is that the collection of values for a random variable obtained by a mathematical model or an experiment fits a particular probability density function. The average results of scientific experiment often must be compared to the expected value of the quantity being measured. Because it is unlikely that the measured and theoretical values will agree exactly, it is necessary to determine if the discrepancy is due to random errors of measurement or if it is due to a systematic difference between theoretical preconceptions and reality.

The distribution of the random variables constituting experimental measurement is usually unknown, and only a small sample from that distribution is available. In such cases the standard deviation a in the above formula should be replaced, the root-mean-square deviation of the replicate measurements from their mean. Because the sample size is small, only an approximation to the true standard deviation and the formula yields a random variable called t-statistics instead. As the two populations is normally distributed, a linear combination of them is also normally distributed. Therefore the two statistics can be used to test if the diference between the two means is significantly different from zero.

Table 1: Comparison of Monte Carlo Integration with SUSYGEN and ISAJET.

Sparticle	*SUSYGEN*	*ISAJET*	χ^2
$\tilde{e}_R^-$	329	302.78	2.41
$\tilde{e}_L^-$	332	320.39	0.45
$\tilde{\nu}_e$	322	308.07	0.62
$\tilde{\nu}_\mu$	322	308.07	0.62
$\tilde{\tau}_1$	109	132.05	4.02
$\tilde{\tau}_2$	375	346.10	2.41
$\tilde{\chi}_1^0$	168.6	172.704	0.13
$\tilde{\chi}_2^0$	529.7	542.466	0.31
$\tilde{\chi}_1^+$	168.601	172.876	0.11
$\tilde{\chi}_2^+$	1196.651	980.340	4.7

Table 2: Masses (GeV) and branching ratios $\mathcal{B}_S$ and $\mathcal{B}_I$ from SUSYGEN and ISAJET.

Sparticle	*SUSYGEN*	*ISAJET*	$\mathcal{B}_S$	$\mathcal{B}_I$
$\tilde{e}_R^-$	329	302.78	1.000	1.000
$\tilde{e}_L^-$	332	320.39	0.222	0.189
$\tilde{\nu}_e$	322	308.07	0.786	0.885
$\tilde{\nu}_\mu$	322	308.07	0.786	0.885
$\tilde{\tau}_1$	109	132.05	1.000	1.000
$\tilde{\tau}_2$	375	346.10	0.453	0.526
$\tilde{\chi}_1^0$	168.6	172.704	0.037	0.031
$\tilde{\chi}_2^0$	529.7	542.466	0.349	0.298
$\tilde{\chi}_1^+$	168.601	172.876	0.864	0.979
$\tilde{\chi}_2^+$	1196.651	980.340	0.056	0.052

7 Discussion and Conclusion

This large number of inputs enters in the evaluation of the masses of SUSY particles and Higgs bosons as well as their complicated couplings, which involve several nontrivial aspects, such as the mixing between diferent states, the Majorana nature of some particles and the higher order corrections which for the calculation of a single parameter need the knowledge of a large part of the remaining spectrum. One has then to calculate in some accurate way, including higher order corrections, the rates for the many possible decay modes and production processes at the various possible machines and eventually the implications for Dark Matter searches. Fortunately, there are well motivated theoretical models where the soft SUSY breaking parameters obey a number of universal boundary conditions at a high (unification) scale, leading to only a handful set of basic parameters. This is the case for instance of the minimal Supergravity model (mSUGRA), where the entire sparticle and Higgs spectrum is determined by the values of only five free parameters, making comprehensive scans of the parameter space and detailed studies of the spectrum feasible. However, there are also similarly constrained and highly predictive models, such as anomaly (AMSB) and gauge (GMSB) mediated SUSY-breaking model, string inspired models or models with righthanded neutrinos, to name a few, which can serve as benchmarks to be investigated. We then have to trade a complicated situation where we have one general model with many input parameters, with a not less complicated situation where we have many constrained models with a small number of basic parameters. In addition, in these unified models, the lowenergy parameters are derived from the high energy (GUT or possibly some intermediate scale) input parameters through Renormalization Group Equations (RGE) and they should also necessarily involve radiative electroweak symmetry breaking (EWSB), which sets additional constraints. The implementation of the RG evolution and EWSB mechanism

poses numerous nontrivial technical problems if they have to be done accurately, including higher order effects. This complication is to be added to the still present one stemming from the accurate calculation of the particle masses and couplings, decay and production rates. Therefore, to deal with the supersymmetric spectrum in all possible cases, one needs very sophisticated programs to encode all the information and eventually, to pass it to Monte Carlo event generators to simulate the physical properties of the new particles. These programs should have a high degree of flexibility in the choice of the model or the input parameters and an adequate level of approximation at different stages, for instance in the incorporation of the RGEs, the handling of the EWSB and the inclusion of the radiative corrections to sparticle masses, which in many cases can be very important. They should also be reliable, quite fast to allow for rapid comprehensive scans of the parameter space and simple enough to be linked with other spectra programs or Monte Carlo event generators.

In the recent years more programs for phenomenological and experimental analyses became available and the tendency to make them public is growing rather fast. This is very useful for the reliability of these tools since many checks and comparisons can be then performed, thus minimizing the number of errors, bugs and inconsistencies. It also generates a healthy competition between the various codes which are more often upgraded to take into account new developments. The programs are becoming more and more sophisticated but at the same time, eorts are devoted to make them more clear, user friendly and with the adequate documentation. Due to the complexity of the subject, most programs deal with only one or a few aspects of the theoretical, phenomenological or experimental facets of SUSY. This calls for complementarity between the various programs for spectra determination, higher order corrections, matrix elements calculations, Dark Matter analyses, Monte Carlo event generators. This leads to more interplay between theory and experiment which is very useful for the field. To summarize, there is a very rapid development of the field. In addition to the fact that many new codes have appeared and many developments in the major spectra codes and Monte Carlo generators have occurred in the recent years, the trend is to make them much faster, more efficient, userfriendly and as complete as possible. Therefore, we will be certainly ready to analyse the data for the next round of experiment. The hope is that SUSY is also ready to be discovered.

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